# Cycling-specific isometric resistance training improves peak power output in elite sprint cyclists

Running title: Isometric training improves PPO in elite cyclists

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## ABSTRACT

**Introduction.** This study aimed to assess the efficacy of a six-week cycling-specific, isometric resistance training programme on peak power output (PPO) in elite cyclists.

**Methods.** Twenty-four elite track sprint cyclists were allocated to EXP (n=13, PPO, 1537 ± 307 W) and CON (n=11, PPO, 1541 ± 389 W) groups. All participants completed a six-week training programme; training content was identical except participants in the EXP group replaced their usual compound lower body resistance training exercise with a cycling-specific, isometric resistance training stimulus. Cycling PPO, knee extensor and cycling-specific isometric strength, and measures of muscle architecture were assessed pre- and post-training.

**Results.** In EXP, absolute and relative PPO increased (46 ± 62 W and 0.8 ± 0.7 $W{\cdot}kg^{-1}$, $p < 0.05$), and the change in relative PPO was different to CON (–0.1 ± 1.0 $W{\cdot}kg^{-1}$, group × time interaction $p = 0.02$). The increase in PPO was concurrent with an increase in extrapolated maximal torque in EXP (7.1 ± 6.5 N·m, $p = 0.007$), but the effect was not different from the change in CON (2.4 ± 9.7 N·m, group × time $p = 0.14$). Cycling-specific isometric strength also increased more in EXP (group × time $p = 0.002$). There were no other between-group differences in response to training.

**Conclusion.** A six-week novel, cycling-specific isometric resistance training period improved PPO in a group of elite sprint cyclists by 3-4%. These data support the use of a cycling-specific isometric resistance training stimulus in the preparation programmes of world-class cyclists.

**Key words.** Muscle; strength, track cycling, isovelocity, knee extensors

## INTRODUCTION

Sprint track cycling is a sport where success is highly dependent on an athlete's ability to generate high levels of external mechanical power output. Previous research has observed a strong association between peak power output (PPO) and cycling speed, and *ergo* cycling performance [1-3]. Implementation of appropriate training to improve PPO is therefore critical to improve sprint track cycling performance [4].

In order to positively influence cycling PPO elite track cyclists routinely employ resistance training that is aimed at improving muscle size and strength, as these variables are associated with the ability to produce high PPO [1,4-7]. These resistance training routines typically employ traditional multi-joint isoinertial exercises such as squat and deadlift variations with heavy loads; this approach is associated with improvements in the ability to generate high levels of force and/or lift heavy external loads, particularly in the trained task. A limitation of these traditional exercises, is that the load imposed is limited by the athlete's concentric strength, and their ability to tolerate repeated movement of very high external loads, both acutely and as part of long-term training. The requirement to frequently and repeatedly exercise with heavy external loading is a particular challenge for very well-trained strength athletes, where even small improvements in physical qualities are very difficult to provoke [8]. The transfer of training effect from improvements in isoinertial strength to cycling PPO, is also questionable. Given the lack of dynamic correspondence between traditional isoinertial strength exercises and sprint cycling [9], coupled with the highly-trained nature of the population, more specific means of training might be required [10].

Cycling-specific isometric resistance training potentially offers a training strategy with greater specificity to cycling than traditional isoinertial resistance training, where the ability to develop force is limited by the athlete's concentric strength through a specific range of motion. Cycling-specific resistance training requires athletes to execute maximum isometric muscle actions in cycling-specific positions; because of the mode of muscle action this approach affords cyclists an opportunity to develop maximum levels of force at cycling-specific joint angles, and reduces the requirement to handle very heavy loads typical of traditional isoinertial training. We have previously demonstrated a very strong association between maximal torque production during a cycling-specific isometric task, and cycling PPO [11]; this finding raises the possibility that improving cycling-specific isometric strength might offer a positive transfer to cycling PPO. Maximum isometric strength training has previously been demonstrated to result in rapid improvements in maximum strength, but adaptations are specific to the joint angle [12-14] and range of motion [15] at which training is performed. Cycling-specific isometric resistance training offers greater specificity to cycling in terms of joint angle, and the subsequent muscle groups recruited, and offers potential for expression of maximum levels of force in cycling-specific positions. As such, cycling-specific isometric resistance training could provide a novel means to elicit improvements in PPO in very well-trained cyclists.

The primary aim of this study was to assess the efficacy of a six-week cycling-specific isometric training regime on PPO, muscle structure, and other indices of muscle function, in a group of elite track cyclists. We hypothesised that the novel, cycling-specific isometric training stimulus would elicit improvements in the PPO of already very well-trained athletes. We further hypothesised that these changes would be concurrent primarily with changes in muscle function rather than muscle structure, given the duration of the training programme.

## MATERIALS AND METHODS

### Participants

Following institutional ethical approval from Northumbria University Research Ethics committee, 24 track sprint cyclists (17 males, 7 females, age, 23 ± 3 yr; mass 80.8 ± 10.9 kg, stature 172.0 ± 9.4 cm) gave written informed consent to participate. The 200 m personal best time for the males (n = 13) was between 9.6 to 10.8 s (within 1 – 12% of the sea-level World Record) and for the females (n = 5) was 10.9 to 12.0 s (within 3 – 11% of the sea-level World Record). Two men's (n = 4) and one woman's tandem (n = 2) also participated in this study. The able-bodied pilots competed individually on their solo bikes and were of an elite standard in their own right; the stokers were visually impaired but otherwise able-bodied. The male tandems had personal best 200 m times of 9.6 (current World Record) and 9.9 s, whilst the women tandem had a best 200 m time of 10.6 s (current World Record). Of the sprinters, four had participated in two Olympic games, winning three Gold medals, and one Silver, and one Bronze medal. Thirteen had competed in senior World Championships winning four silver medals. The tandem pilots and stokers had participated in three Paralympic games, winning two Gold, one Silver, and one Bronze medal, as well as having participated in nine World Championships, winning a total of twenty-one medals. The remaining were either competing internationally at UCI Class One or Two track competitions, World Cups, senior or under-23 level or had won a National medal in a track sprint event.

### Design

The study utilised a parallel group, control trial design to study the effects of a 6-week cycling-specific isometric strength training regime. Participants were allocated to experimental (EXP) and control (CON) groups prior to commencement of the study. Full random allocation of participants was not possible because of logistical challenges with implementing a novel resistance training intervention with an elite population. Menstrual cycle phase was not controlled for the same reasons. All the sprint riders who participated in this study did so after 1-2 weeks off from any structured training followed by a two-week 're-introduction' period during which the athletes slowly and progressively resumed their normal full training schedule. All participants had a minimum of two years history of resistance training. Riders were divided into two groups: "current best practice" controls (CON; n = 11, 9 male, 2 female), largely comprised of 'podium-level' international sprinters, and experimental (EXP; n = 13, 8 male, 5 female), composed of current international under-23 programme, national level, and 'podium-level' riders. There were no differences at baseline between groups in absolute and relative peak PPO (Table 1). The "best practice" CON group performed their habitual training routines, while the EXP group performed an identical programme with the exception of inclusion of cycling-specific isometric strength training in place of their usual regular heavy isoinertial multi-joint lift (described in greater detail below). The study was conducted out of the competitive season during a designated "maximum strength" phase of the preparation programme.

Pre- and post- the 6-week training programme, participants completed a battery of assessments in the following order: i) dual-energy x-ray absorptiometry (DXA) scan to assess body composition; ii) ultrasound assessment of *vastus lateralis* to assess architecture; iii) neuromuscular assessment for measurement of knee extensor isometric maximum voluntary force (MVF), rate of torque development (RTD), and voluntary activation (VA); iv) assessment of cycling-specific isometric MVF (ISO-CYC); v) isovelocity sprint-cycling assessment to measure PPO, torque-cadence, and power-cadence relationships. All participants performed familiarisation trials for every assessment which preceded the experimental trials. The testing battery was completed after 36 hours of rest pre- and post-training. Post-training assessment was conducted at the same time of day (±1 hour), on the same day of the week, as the pre-test. All testing was conducted in laboratory facilities at the English Institute of Sport within the National Cycling Centre, Manchester. Participants were instructed to refrain from caffeine on the day of testing, and to avoid eating 2 h prior to testing.

## Procedures

### *Body composition assessment*

Participants reported for body composition assessment wearing appropriate clothing (i.e. loose-fitting gym attire), which would allow proper scanning of the entire body. After voiding their bladder and bowel, Whole-body DXA scans (Lunar iDXA; GEHealthcare, Madison, WI) were conducted using a standardised protocol while participants lay supine on the scanner, which was calibrated daily. Body mass (kg), total lean mass (kg), lower body lean mass (kg), and body fat (%) were recorded. After DXA assessment, participants ate, then reported to the lab 2-3 h later for the remainder of the testing battery.

### *Ultrasound assessment*

Assessments of muscle structure were performed by using brightness-mode ultrasound (B-mode) images. A linear array transducer (5-10 MHz, scanning width 92 mm, and depth 65 mm, EUP-L53L; Hitachi EUB-8500) was used to form B-mode images of the superficial muscle whilst participants sat on a custom-made dynamometer for measurement of knee extension force (detailed below). Water-soluble transmission gel was used to coat the transducer that was positioned with minimal pressure on the skin. Images were captured with the transducer placed on the medial longitudinal line of the muscle while positioned on the skin over the *vastus lateralis* at 50% of femur length (from the knee joint space to the greater trochanter) to correspond with the area of greatest anatomical cross-sectional area. The transducer was orientated perpendicular to the skin and parallel to the fascicular path. Both legs were assessed. Ultrasound images were imported into analysis software (ImageJ, v.1.46; National Institutes of Health, Bethesda, MD, USA) to measure *vastus lateralis* muscle thickness ($MT_{VL}$) and pennation angle ($P\theta_{VL}$). The $P\theta_{VL}$ was measured as the angle between the fascicular path and the insertion of fascicles into the deep aponeurosis. Muscle thickness was measured as the distance between the superficial and deep aponeurosis. A plastic sheet was put over the thigh and any individual marks or scars on the thigh were marked using a permanent marker pen, along with where the transducer was in relation to the marks. This was used in the post-testing to ensure the images were acquired in the same position. Three different ultrasound images for each leg were assessed, with the average score of all six images taken for analysis. The intra-rater repeatability of the measurements of $P\theta_{VL}$ had a typical error (CV) of 4.1% and intraclass correlation (ICC) of 0.86, and $MT_{VL}$ had CV of 2.2% and ICC of 0.91.

*Neuromuscular assessment*

Participants were positioned in a custom-built isometric dynamometer with the hip joint angle at ~125° and the knee joint angle at ~115° (full extension for both hip and knee was assumed to be 180°). Participants were securely fixed in place by three separate industry-standard polyester seatbelts with adjustable automotive seatbelt latchets placed over each shoulder, and the hip. A calibrated S-beam strain gauge (Force Logic, Swallowfield, UK) was used to measure force. A metal cuff attached to the strain gauge was positioned perpendicular to the tibia and attached to the ankle (~15% of tibial length above the medial malleolus). Another two straps, 40 mm in width and made of reinforced canvas webbing, were placed over the cuff to further secure it. The analogue force signal from the strain gauge was amplified (×370) and sampled (2,000 Hz) using an external analogue-to-digital converter (Micro 1401; CED, Cambridge, UK) and recorded with Spike2 computer software (CED, Cambridge, UK). force data were gravity corrected by subtracting the baseline force and multiplying by the lever length i.e. the distance from the knee joint space to the centre of the ankle strap, to calculate knee joint torque values.

For measurement of MVF and VA, participants initially completed 5 s isometric actions at 50, 75, and 90% of perceived maximum, separated by 60 s of rest. Subsequent to this, single electrical stimuli (200 $\mu$s duration) were delivered to the femoral nerve via 50 mm disposable self-adhesive surface electrodes (A.CF5000, Digitimer Ltd., Welwyn Garden City, Hertfordshire, UK), connected to a constant-current stimulator (DS7AH, Digitimer Ltd., Welwyn Garden City, Hertfordshire, UK). The anode was placed midway between the iliac crest and the greater trochanter, and the cathode was placed high in the femoral triangle, over the femoral nerve. Stimulations commenced at 50 mA and were incremented by 25 mA until a plateau in twitch force was observed; to ensure the stimulus was supramaximal the resulting current intensity was increased by 30% for all subsequent stimulations (mean intensity 355 ± 32 mA).

Participants performed three, five second, isometric knee extension actions separated by 60 s of rest. During the isometric action, single electrical stimuli were delivered at the plateau in maximum force for assessment of the superimposed twitch force, and 2 s post to the relaxed muscle for assessment of quadriceps potentiated twitch force. Strong verbal encouragement was given for the duration of each effort. The highest maximum torque was recorded as MVF. Voluntary activation was calculated from all three manoeuvres as previously described, with a correction factor applied where stimulation during the MVF was submaximal (less than 95%

of MVF) [16]. The reliability (CV, ICC) of these assessments is 4.1%, 0.96, 3.2%, 0.88, and 4.8%, 0.87 for MVF, voluntary activation, and potentiated twitch respectively.

Subsequent to MVF assessment, and after 5 min of rest, participants completed 10 × 1 s isometric knee extension actions with instruction to extend their knee "as fast and as hard as possible" for the assessment of RTD. Participants were instructed to avoid any countermovement or pre-tension; this was monitored by the lead investigator using a custom-made script that highlighted any deviation from baseline. Biofeedback to the cyclists was provided by a real-time force-time curve on a monitor. This provided the cyclists with a visual display to inform them as to whether any pre-tension or countermovement was made, and to provide the force recorded at 200 ms a source of motivation and gauge for previous and subsequent efforts. The highest 3 torque measurements at 50, 100, 150 and 200 ms from when torque onset breached 2% of MVF for each leg was used and averaged to quantify RTD [17]. The CV for RTD ranged from 2.9 to 3.2%, and ICC ranged from 0.81 to 0.93.

*Cycling-specific isometric maximum voluntary torque (ISO-CYC)*

Following RTD assessment (5 min passive rest), participants mounted a custom-built cycle ergometer (BAE systems, Farnborough, UK) to measure their maximum isometric cycling-specific torque (ISO-CYC). The ergometer was adjusted to match the cyclists track bike position (see Figure 1 for image of set up). Prior to maximum isometric efforts, participants were permitted a 3 min warm-up at 100-150 W. To make the ergometer isometric, a car jack clamp was fitted with a rubber stopper and attached to the ergometer by pressing against the flywheel. The crank arms were fixed at 90° clockwise and anti-clockwise from top dead centre. As the ergometer was individually adjusted to replicate the riders track bike position, hip and knee angles varied slightly between participants; we considered this approach a more ecologically valid estimate of cycling-specific isometric strength, and subsequently employed the same approach to cycling-specific isometric resistance training (described below). Participants were instructed to try to pedal the ergometer with both legs "as hard as possible". The ergometer was fitted with instrumented cranks (Factor Cranks, BF1 Systems, Diss, UK) that continually recorded torque, hence they were able to record isometric efforts. For all efforts, the cyclists had real-time feedback on the torque produced through the crank arms via custom-made software (CrankCam, Sports Engineering Department, Sheffield Hallam University, UK). Participants were asked to rest their forearms on the 'tops' of the handlebars to ensure that movement from the upper body contribution, and changes in lower body joint angles, were minimised, and to stay seated during maximum efforts. Prior to performing any efforts, a seatbelt was positioned on the first contact point of their left buttock and the seat with a 1.25 kg weight placed on the other end to ensure the cyclists stayed in the saddle; if they got out of the saddle, the belt weight would fall to the floor and the effort would not be recorded. Participants completed three ISO-CYC maximum efforts on their dominant leg, lasting 3-5 s each, with 60 s separating efforts, before resting 3 min and repeating the protocol with their non-dominant leg. Force-time data was wirelessly transmitted and recorded (BF1-Logger, BF1 Systems, Diss, UK) at 192 Hz, and analysed by off-line software (Spike2, CED, Cambridge, UK) using custom-made scripts. The effort with the highest peak instantaneous cumulative (i.e. sum of right and left crank) mechanical torque output (for each side) was used for analysis. The reliability of this assessment is good (CV = 3.9%)[18].

*Isovelocity sprint cycling test*

Torque-cadence and power-cadence relationships were assessed from an isovelocity sprint cycling test performed on a modified ergometer (Schoberer Rad Messtechnik, Jülich, Germany). The ergometer was modified for each individual to match their track bike racing position. All efforts were performed seated whilst using the "drop" handlebars. Participants performed 4 s maximal efforts at fixed cadences of 60, 115, 125, 135, and 180 RPM, with 3 min passive rest in between. The order of cadences was selected at random and prescribed in the same order for each participant (115, 60, 135, 125 and 180 RPM). The cadence remained constant by using a braking module and a 2.2 kW motor, and the ascent to the prescribed cadence was motor-driven so that participants were able to pedal to the prescribed cadence with no external resistance. Participants were given instructions to "attack the effort as fast and as hard as possible" throughout each sprint, and strong verbal encouragement was provided. The maximum power output over three consecutive revolutions, measured from top dead centre, at each cadence was averaged for each cadence. From that, power-cadence and torque-cadence relationships were established by fitting a quadratic and linear equation, respectively, by the least square method, as used previously [1,19,20]. The apex of the power-cadence relationship was interpolated to derive PPO and cadence at PPO. Maximal torque and maximal cadence were extrapolated from individual torque-cadence relationships ($r^2 = 0.99 \pm 0.01$), and are presented in absolute terms, and relative to body mass. Reliability of PPO (CV = 2.7%, ICC = 0.96), maximal torque (CV = 3.6%, ICC = 0.94), and maximal cadence (CV = 4.0%, ICC = 0.83) in our laboratory has previously been reported [21].

*Training intervention*

All participants completed a 6-week training intervention. In both EXP and CON, participants were prescribed weekly track cycling sessions (n = 2, Tuesday & Thursday), gym sessions (n = 2-3 Monday, Wednesday (alternating with road sessions), and Friday, and road rides (n = 1-2, Wednesday (alternating with gym sessions), and Saturday. Training was identical between groups except for the content of the gym sessions. The track sessions consisted of a "high torque" day (stationary or slow-moving maximal efforts of 3-12 reps of 6-20 s), and a "high power" day (3-5 reps of 10-35 s where efforts were commenced from higher cadences and velocities). Road sessions were 60-90 mins in duration at a perceived effort of 2-4 on the Borg category-ratio 10 scale.

For gym sessions, in CON participants were prescribed a bilateral, compound, multi-joint exercise to develop leg strength (back squat, front squat, or deadlift depending on rider preference) with 3 to 5 sets of 3 to 5 repetitions at an intensity equivalent to 85-95% of their 1RM, with a 2-3 s descent, a maximal mobilisation of load in the concentric phase, and complete recovery (3-5 min) between sets. The load selected was designed to be challenging to the athlete but did not result in momentary muscle failure. As the group studied were elite cyclists, it was not possible to precisely control their programming, however the resistance training stimulus was targeted at developing maximum strength (i.e. low repetitions, high load, long recovery) for all participants, with the exact stimulus individualised within the boundaries outlined. This was followed by three sets of another multi-joint exercise with similar loads such as cleans or barbell jumps, dumbbell lunges, or single or double leg-press. After the two main exercises, unilateral exercises (knee extensions, hamstring curls, calf raises) were completed but were higher in volume (6 – 12 repetitions) and lower in load (~70 – 90% of predicted 1 RM), followed by auxiliary exercises focussed on conditioning the trunk. The EXP group gym sessions consisted of a progressive maximal cycling-specific isometric strength training stimulus. Participants performed in 3 separate positions for each lead leg: 45$^{o}$, 90$^{o}$ and 135$^{o}$ from top dead centre; these angles are associated with the highest torque production during the crank cycle[1]. All efforts were maximal, and 3 s in length to allow attainment of maximum torque on each repetition. Participants performed 1 set of 3 repetitions, at each of the 3 joint angles in week 1, progressing to 2 × 4 in week 2, 3 × 3 in week 3, 4 × 3 in week 4, 4 × 3 and 4

× 4 in week 5, and 4 × 4 in week 6. Between each rep, 60 s of passive rest was given. Between each set (and crank position change) 2 min of passive rest was given. Exercise was prescribed to alternate lead legs at each position; e.g. 3 sets on the right leg at 45 °, followed by 3 sets with left leg leading at 45°. The order of angles was randomly prescribed on each visit. For all efforts, real-time visual feedback on the torque produced through the crank arms was provided to motivate a best attempt. As part of the arrangement with the coaches of the sprinters in the EXP group for them to participate in this study, it was agreed that the EXP sprint cyclists would perform 3 sets of 5 reps of the back squat exercise at ~70 - 75% of predicted 1RM, with maximum mobilisation in the concentric phase, and 3 minute rest in between sets, after the isometric training protocol. This was to ensure that, should the intervention not augment any positive improvements in PPO and sprint performance, the sprinters would then have attenuated any regression in their habitual gym training. The EXP group finished each gym session with the same auxiliary exercises for trunk conditioning as CON. All sessions in CON were supervised by the athlete's strength and conditioning coach and the lead researcher, and the ISO-CYC sessions in EXP were supervised by the lead researcher.

**Statistical analysis**

Data are reported as mean ± standard deviation (SD). Where appropriate, data are normalised to body mass in addition to absolute scores. Reliability statistics reported were calculated as typical error [22] and $ICC_{3,1}$. Mixed factorial, 2 × 2 (Group; EXP, CON, by Time; pre-, post-) ANOVA were employed to assess differences between groups, and the effect of the training intervention. Between-group comparisons of baseline scores, and pre- to post- within-group changes in EXP and CON, were made with Bonferroni adjustments. Effect sizes for selected within-group comparisons were calculated using Cohen's *d* (mean difference divided by pooled standard deviation). Relative (%) changes in the PPO were correlated with relative (%)

changes in the outcome measures which are purported to underpin PPO using Pearson's *r*. Assuming no multi-collinearity, variables which were significantly correlated with the improvement in PPO were entered into a step-wise multiple regression. All analysis was performed with SPSS software, the threshold for statistical significance was $p \leq 0.05$.

## RESULTS

**Isovelocity cycling.** At baseline, absolute and relative PPO in EXP (1537 ± 307 W, 18.7 ± 2.5 W·kg$^{-1}$) were not different to CON (1541 ± 389 W, 19.0 ± 3.5 W·kg$^{-1}$). Absolute PPO increased pre- to post-training in EXP (46 ± 62 W, 3 ± 4%, $d = 0.17$, $p = 0.05$) but not in CON (−5 ± 98 W, 0 ± 6%, $p = 0.844$, Table 1). The increase in absolute PPO in EXP was not statistically different from the change in CON (group × time interaction $p = 0.14$). Peak power output relative to body mass increased more in EXP compared to CON (group × time interaction $p = 0.02$), with pre- to post changes of 0.8 ± 0.7 W·kg$^{-1}$ ($p = 0.004$) and −0.1 ± 1.0 W·kg$^{-1}$ for EXP and CON, respectively (Figure 2). Ten out of 13 participants in EXP increased their relative PPO by >2% (Figure 3); the average change was 4 ± 5%, ranged from −1% to 16%, and amounted to a small effect ($d = 0.33$). In CON, two participants increased their relative PPO by >2% (Figure 3), the average change was 0 ± 5%, ranged from −8% to 7%, and amounted to a trivial effect ($d = -0.05$) The changes in PPO were concurrent with an increase in extrapolated maximal torque in EXP (7.1 ± 6.5 N·m, $p = 0.007$, Table 1), but the effect was not statistically different from the change in CON (2.4 ± 9.7 N·m, group × time $p = 0.14$). Extrapolated maximal cadence did not change in EXP ($p = 0.70$, Table 1) or CON ($p = 0.36$, Table 1), nor did cadence at optimised PPO ($p = 0.99$ and 0.27 for EXP and CON respectively, Table 1, Figure 2), with no significant group × time interactions.

**Anthropometric, neuromuscular and isometric strength changes.** There were no pre- to post- differences in body mass, lean body mass, lower body lean mass, or body fat in either EXP or CON (Table 1 & 2). Pennation angle increased over time in both groups ($p < 0.001$); the change in CON (6.4%) compared to EXP (5.2%) approached significance (group × time $p = 0.06$). Muscle thickness increased in both groups ($p = 0.034$), with no difference between groups (group × time $p = 0.66$). No differences were observed for isometric knee extensor MVF and VA in either group (Table 2). For RTD, training had no effect on the early RTD (torque at 50 and 100 ms was unchanged) but torque at 150 ms and 200 ms was increased in EXP ($p$ = 0.03 and 0.003, respectively; Table 2); this change was not different to CON (group × time interaction $p$ = 0.18 and 0.054 for torque at 150 ms and 200 ms, respectively). Cycling-specific isometric maximum voluntary torque increased in EXP by 12.5% ($p = 0.001$, Table 2), which was larger than the change in CON (group × time interaction $p = 0.002$), where ISO-CYC was unchanged ($p = 0.27$).

**Regression analysis.** Changes in each outcome measure were correlated with the change in PPO across all participants; only changes in RTD (torque at 150 and 200 ms) were significantly related with the change in PPO (Table 3, Figure 4). Multiple regression of these outcome measures to predict PPO was not performed due to a high correlation between changes in $Torque_{150}$ and $Torque_{200}$ ($r = 0.92$, $p < 0.001$).

## DISCUSSION

The implementation of a 6-week cycling-specific, isometric resistance training programme improved cycling peak power output in a group of world-class sprint cyclists. The change in PPO was mediated by an increase in the extrapolated maximum torque elicited from isovelocity cycling, and concurrent with an increase in cycling-specific isometric torque, and the rate of torque development measured during isometric knee extension. From these data we conclude the application of a novel, cycling-specific isometric resistance training period can provide the necessary stimulus to improve PPO in elite track cyclists.

**Increases in cycling peak power output.** On average, cyclists in the experimental group increased their PPO, and relative PPO, by 3% and 4%, respectively. In contrast, participants in the control group, who completed a "best practice" control intervention consisting of their regular resistance training programme, showed no improvement (0% on average for both absolute and relative PPO). Although the magnitude of change in the experimental group appears relatively small, and indeed the change in absolute PPO did not exceed that observed in the control group, these data should be interpreted relative to the world-class status of this group of athletes. The pre-test values for PPO and relative PPO (1537 W, 18.7 $W \cdot kg^{-1}$) for the experimental group (which included five females) compare favourably to previously published data on male world-class sprint cyclists (1600 W, 19.3 $W \cdot kg^{-1}$) [1]. Additionally, the experimental group included riders who were current world and Olympic record holders, and had previously won medals at World, Olympic, and Paralympic games. It is well-recognised that provoking improvements in sport performance in already elite athletes is very difficult to achieve [8], and even more difficult to measure [23]. Considering this context, the changes in PPO observed as a consequence of cycling-specific isometric training are pronounced, and support the use of this novel training strategy in elite populations.

**Transfer of training.** The improvement in cycling PPO was mediated by an increase in the theoretical maximum cycling torque, which is consistent with the isometric training stimulus employed, and the improvements observed in cycling-specific isometric torque in the experimental group. The cycling-specific resistance training consisted of repeated maximum isometric actions where cyclists sat in their racing position, on a cycle ergometer, and were required to generate maximum torque at three different pedal angles. The training stimulus is ostensibly task-specific to an extent; offering the opportunity for riders to repeatedly produce sustained maximum forces in cycling-specific positions and therefore offering an overload stimulus, given that maximum levels of force during track cycling would typically either be unattainable (because of movement velocity and muscle action type) or unsustainable (because of movement time constraints). Previous work has also demonstrated isometric resistance training to be efficacious, but relatively specific to the joint angle at which the training was performed [12,13]. To maximise the transfer of training in the present study, we employed isometric actions at three different angles, to provoke increases in the ability to produce force across the pedal stroke. The concurrent improvement in PPO and theoretical maximum torque is consistent with previous work studying the *adductor pollicis* muscle, where increases in PPO after an isometric training program were also mediated by the theoretical maximum extrapolated force [24]. The training regime employed in the present study therefore offered an innovative overload strategy to stress the cyclists ability to produce maximum levels of force in cycling-specific positions, which provoked an increase in PPO by improving the maximum torque observed in the underpinning torque-velocity relationship.

**Muscle function and structure changes.** Peak power output in cycling is proposed to be underpinned by muscle strength, size, and structure [3,25]. The relationship between indices of muscle function and structure are well-established in heterogenous populations [4,5], but less-so in homogenous groups [1]. We hypothesised that changes in muscle function might be concurrent with changes in cycling PPO, but that changes in muscle structure were unlikely given the relatively short duration of training. We observed changes in cycling-specific isometric strength, the late RTD during isometric knee extension, and the pennation angle and muscle thickness of *vastus lateralis*. However, only RTD was correlated with the changes in PPO. The factors that underpin the RTD at late intervals (i.e. 150-200 ms) are proposed to be mediated by speed-related and maximal voluntary force-related properties of muscle [26,27]; a posit that is consistent with the changes in the torque-velocity relationship observed in the experimental group. However, the variance explained (18-22%) by changes in RTD was still relatively low, and voluntary activation was unchanged in both groups. Muscle thickness of the VL increased in the CON group, and pennation angle increased in both groups, though these changes were small in magnitude (Table 1). The increase in muscle thickness in CON suggests that the traditional isoinertial resistance training was a more potent stimulus for local hypertrophy, however this did not translate to an improved PPO, whereas specific isometric resistance training did. Collectively it is plausible that the changes in PPO were underpinned by a combination of factors, but the homogeneity and small changes observed in all of the outcome measures preclude meaningful inference.

A limitation of the present study was the lack of random allocation to groups. Random allocation is a key principle underpinning control trial designs which is required to reduce bias. In this study, random allocation was not possible because of logistical reasons and constraints on training manipulation for some athletes. Participants were allocated to experimental and control groups based on decisions made by their head coach regarding the availability of athletes, their current training schedule and location (as the ergometer was based at a central venue), and the perceived willingness of the cyclists to accept an innovative addition to their programme. In this respect, neither the experimenter nor the participant had an explicit contribution to the allocation decision, but we cannot discount a possible bias inherent in the coaches approach. This limitation was a necessary concession in order to have the opportunity to manipulate the training of a group of world-class athletes. Similarly, it was not possible to precisely control the entirety of the training stimulus for all riders. Individual coaches and athletes expressed preference for certain exercise selection and loading schemes; therefore training might have varied slightly between athletes but, importantly, they were within a fairly narrow range (3-5 sets of 3-5 repetitions at 85-95% 1RM), and all were targeted to develop of maximum strength. Conceptually, as this approach was aimed at optimising adaptation for each individual athlete it could be more efficacious than a “blanket” stimulus which would increase experimental control but might not necessarily be optimal for all athletes. Regardless, the replacement of the athlete’s primary compound lift with a specific isometric stimulus still represented the major difference between groups and is likely the explanatory factor for the results observed.

## PERSPECTIVE

This work represents a rare example of the application of a training methodology in a group of world-class athletes; specifically, a six-week cycling-specific, isometric resistance training programme provoked marked improvements in cycling peak power output in this elite population that were mediated by increases in maximum torque. The results of this work provide support for the implementation of a novel, tolerable, effective, resistance training method in the programmes of world-class track cyclists. Future research is warranted to establish the mechanisms underpinning improvements in peak power output, in order to better understand how to target specific adaptation to improve sprint cycling performance in elite athletes. Notwithstanding, these data clearly demonstrate the non-trivial improvements in PPO that are possible from a short-term intervention in a group of world class athletes.


## Acknowledgements

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Table 1. Pre- and post- body mass and isovelocity sprint test measures for experimental (n = 13) and control (n = 11) groups. Values are mean ± standard deviation.

| | EXP | | | | | | | CON | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pre- | | | Post | | | % change | Pre- | | | Post | | | % change |
| Body mass (kg) | 82.1 | ± | 13.1 | 81.1 | ± | 12.0 | −1.2 | 80.2 | ± | 8.3 | 80.6 | ± | 8.0 | 0.5 |
| PPO (W) | 1537 | ± | 307 | 1581 | ± | 287* | 2.9 | 1541 | ± | 389 | 1536 | ± | 366 | −0.3 |
| PPO:BM ($W \cdot kg^{-1}$) | 18.7 | ± | 2.5 | 19.5 | ± | 2.3*# | 4.3 | 19.0 | ± | 3.5 | 18.9 | ± | 3.1 | −0.5 |
| Maximum torque (N·m) | 207 | ± | 32 | 214 | ± | 32* | 4.2 | 194 | ± | 34 | 196 | ± | 34 | 1.0 |
| Maximum cadence (rpm) | 276 | ± | 18 | 277 | ± | 19 | 0.4 | 289 | ± | 12 | 284 | ± | 24 | −1.7 |
| Optimal cadence (rpm) | 138 | ± | 9 | 138 | ± | 9 | 0 | 144 | ± | 13 | 142 | ± | 12 | −1.4 |

PPO, peak power output; PPO:BM, peak power output relative to body mass. Maximum torque & cadence were extrapolated from the isovelocity cycling assessment
* denotes significant difference between pre- and post- ($p \leq 0.05$), # denotes significant group × time interaction ($p \leq 0.05$)

Table 2. Pre- and post- DXA, ultrasound, neuromuscular and functional measures for experimental (n = 13) and control (n = 11) groups. Values are mean ± standard deviation.

| | EXP | | | CON | | |
|---|---|---|---|---|---|---|
| | **Pre-** | **Post** | **% change** | **Pre-** | **Post** | **% change** |
| Total lean body mass (kg) | 63.8 ± 10.9 | 63.9 ± 10.4 | 0.2 | 63.3 ± 9.6 | 63.5 ± 9.7 | 0.3 |
| Lean lower body mass (kg) | 23.2 ± 4.0 | 23.1 ± 3.8 | −0.4 | 22.6 ± 3.4 | 22.7 ± 3.5 | 0.4 |
| Body fat (%) | 13.2 ± 6.0 | 13.0 ± 6.6 | −0.2 | 13.9 ± 3.9 | 13.7 ± 4.0 | −0.3 |
| $P\theta_{VL}$ (°) | 17.1 ± 2.0 | 18.0 ± 1.7* | 5.2 | 17.1 ± 2.8 | 18.2 ± 2.4* | 6.4 |
| $MT_{VL}$ (mm) | 22.4 ± 2.6 | 23.0 ± 3.0 | 2.6 | 21.9 ± 3.5 | 23.3 ± 3.9* | 6.3 |
| MVF (N·m) | 309 ± 75 | 323 ± 65 | 4.5 | 296 ± 44 | 296 ± 44 | 0 |
| $Torque_{50}$ (N·m) | 115 ± 33 | 118 ± 23 | 2.6 | 114 ± 28 | 109 ± 30 | −4.4 |
| $Torque_{100}$ (N·m) | 189 ± 45 | 196 ± 28 | 3.7 | 184 ± 36 | 183 ± 40 | −0.5 |
| $Torque_{150}$ (N·m) | 227 ± 53 | 240 ± 37* | 5.7 | 226 ± 40 | 227 ± 43 | 0.4 |
| $Torque_{200}$ (N·m) | 241 ± 59 | 260 ± 43* | 7.9 | 242 ± 39 | 244 ± 37 | 0.8 |
| ISO-CYC (N·m) | 400 ± 78 | 450 ± 113*# | 12.5 | 383 ± 98 | 367 ± 82 | −4.2 |
| Voluntary activation (%) | 97.1 ± 2.0 | 97.3 ± 2.4 | 0.2 | 97.6 ± 2.5 | 97.5 ± 2.2 | −0.1 |

$P\theta_{VL}$, *vastus lateralis* pennation angle; $MT_{VL}$, *vastus* lateralis muscle thickness; MVF, maximum voluntary force, ISO-CYC, cycling-specific isometric maximum voluntary torque. * denotes significant difference between pre- and post- ($p \leq 0.05$), # denotes significant group × time interaction ($p \leq 0.05$).

Table 3. Associations between the relative change in peak power output, and the relative change in anthropometric, neuromuscular, and functional outcome measures (n = 24). Statistically significant correlations are highlighted in bold font ($p \leq 0.05$)

| **Predictor variable** | ***r*** | ***p*** | **$R^2$** |
|---|---|---|---|
| Total lean body mass | 0.30 | 0.15 | 0.09 |
| Lean lower body mass | 0.20 | 0.35 | 0.04 |
| $P\theta_{VL}$ | 0.20 | 0.35 | 0.04 |
| $MT_{VL}$ | 0.26 | 0.22 | 0.07 |
| MVF | 0.36 | 0.08 | 0.17 |
| $Torque_{50}$ | 0.26 | 0.22 | 0.07 |
| $Torque_{100}$ | 0.33 | 0.12 | 0.11 |
| $Torque_{150}$ | **0.42** | **0.04** | **0.18** |
| $Torque_{200}$ | **0.47** | **0.02** | **0.22** |
| ISO-CYC | 0.22 | 0.30 | 0.05 |
| Voluntary activation | 0.07 | 0.75 | <0.01 |

$P\theta_{VL}$, *vastus lateralis* pennation angle; $MT_{VL}$, *vastus* lateralis muscle thickness; MVF, maximum voluntary force, ISO-CYC, cycling-specific isometric maximum voluntary torque.

## LIST OF FIGURES

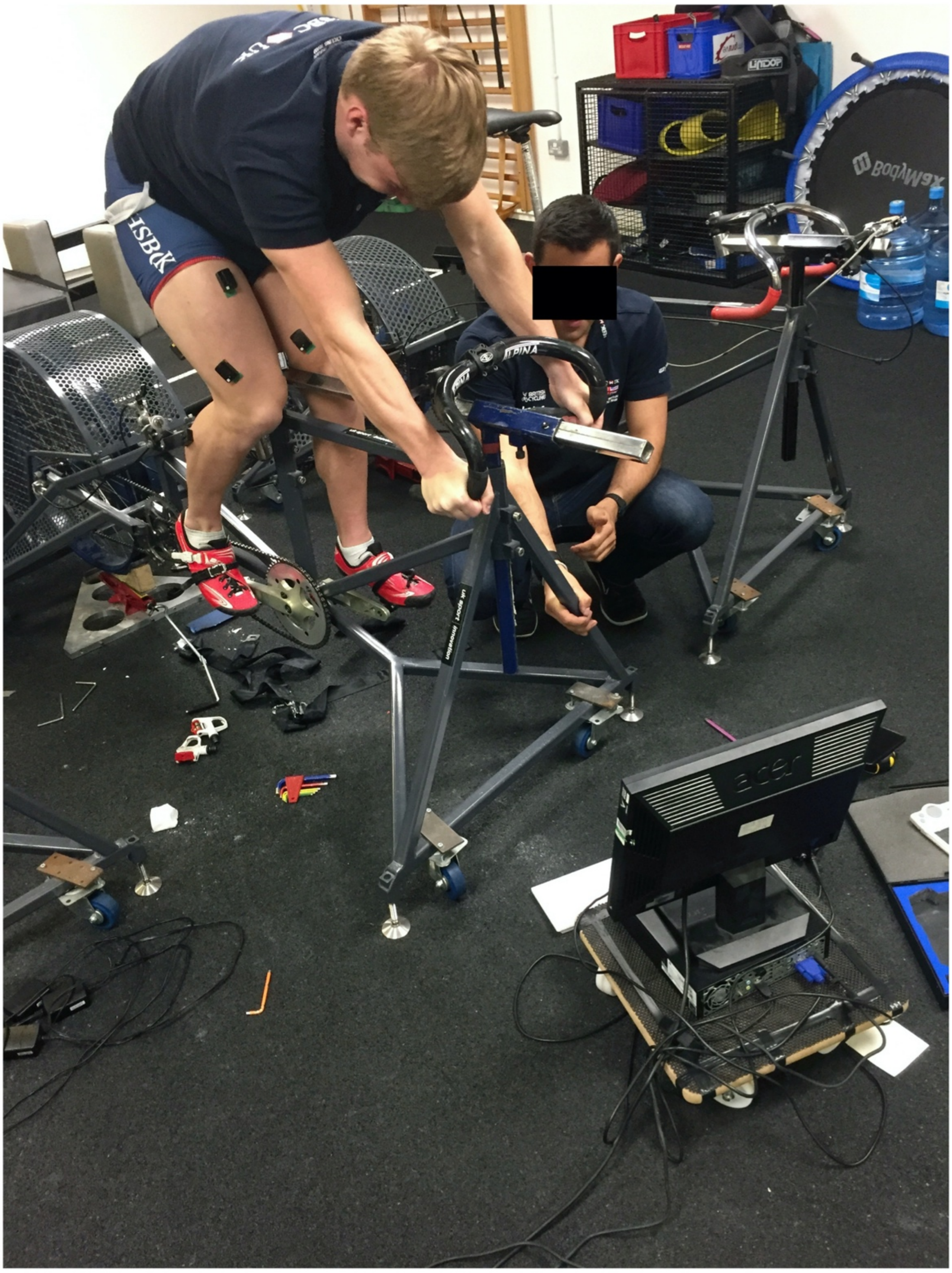


**Figure 1.** An image of a participant performing maximal isometric cycling-specific efforts as part of the experimental group training

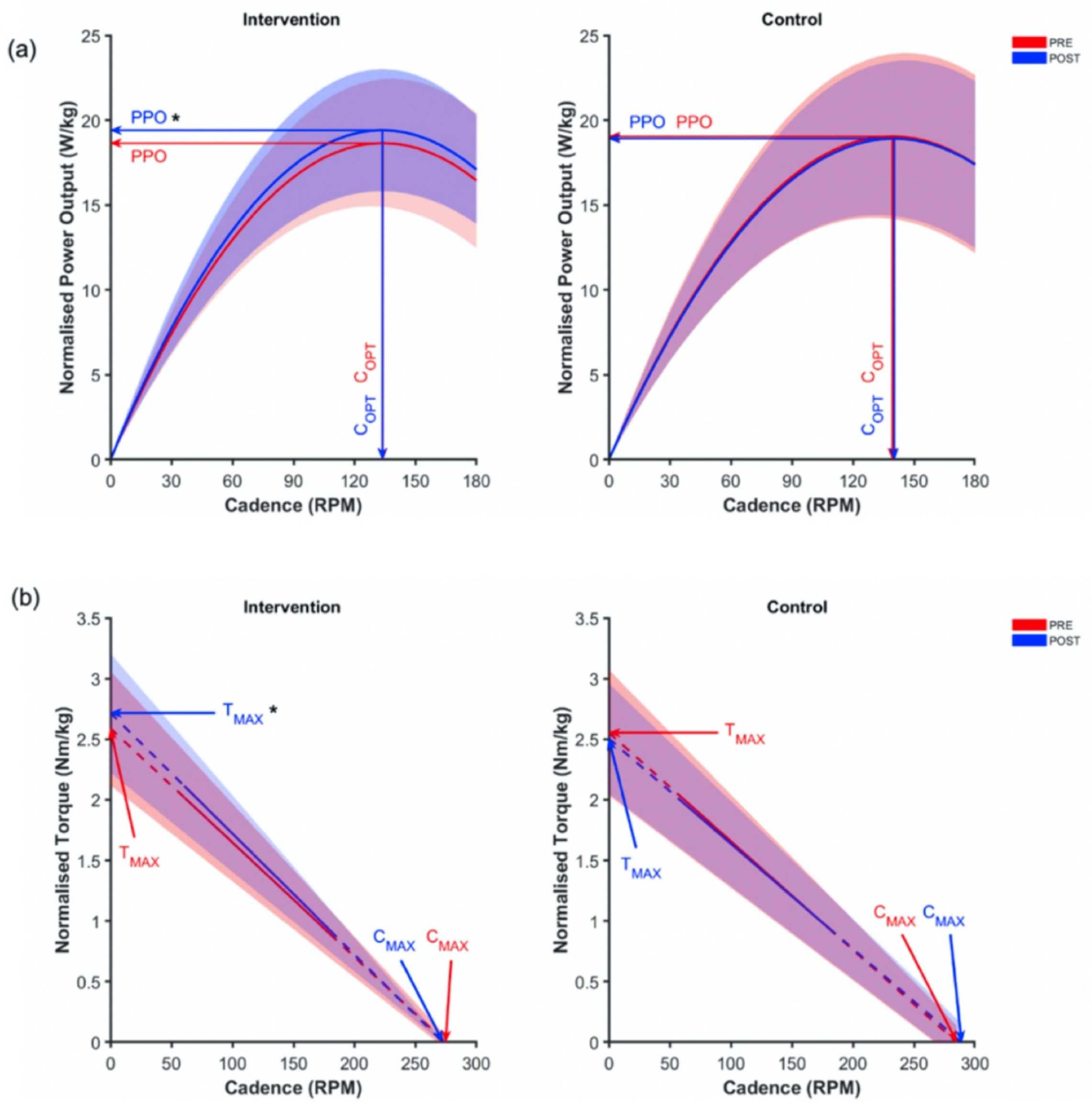


**Figure 2.** Relative (a) power-cadence and (b) torque-cadence relationships pre- and post-training in experimental (n = 13) and control groups (n = 11). Mechanical peak power output (PPO) and optimal cadence (COPT) pre- and post-intervention are annotated on the power-cadence relationship. Maximum extrapolated torque and maximum extrapolated cadence pre- and post-intervention are also highlighted for both groups. Shaded areas represent the standard deviation around the respective means which are represented by solid lines (measured values) and dotted lines (extrapolated values).

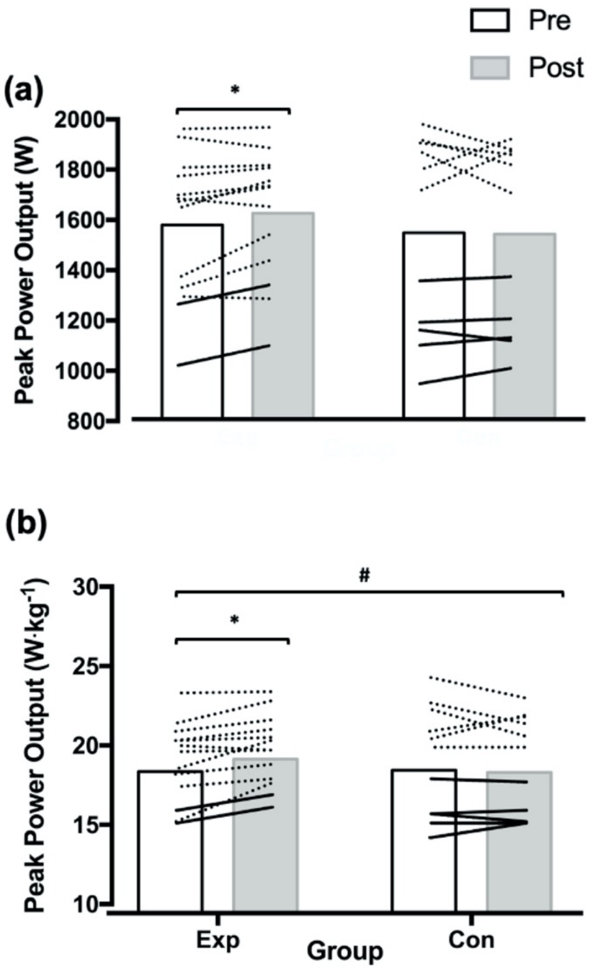


**Figure 3.** Group mean (bars) and individual (lines) changes in (a) peak power output, and (b) peak power output normalised to body mass, in experimental (n = 13) and control (n = 11) groups. Solid lines represent female participants in each group, dashed lines are male participants. * denotes significant difference between pre- and post- ($p \leq 0.05$), # denotes significant group × time interaction ($p \leq 0.05$)

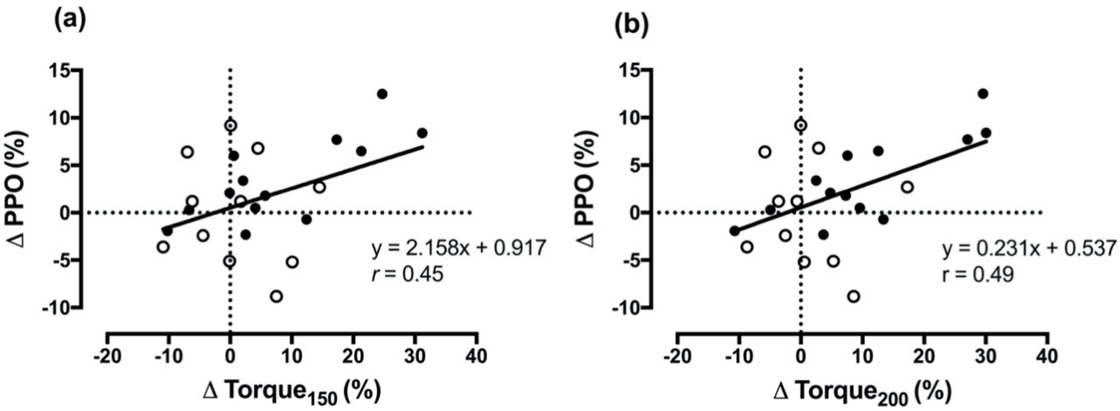


**Figure 4.** Relative (%) changes in peak power output (PPO) vs relative (%) changes in (a) torque at 150 ms, and (b) torque at 200 ms axcross EXP (filled circles) and CON (open circles) groups (n = 24).

## References


1. Dorel S, Hautier CA, Rambaud O, et al. Torque and power-velocity relationships in cycling: relevance to track sprint performance in world-class cyclists. Int J Sports Med. 2005;26(9):739-746.
2. Weyand PG, Lin JE, Bundle MW. Sprint performance-duration relationships are set by the fractional duration of external force application. Am J Physiol. 2006;290(3):R758-765.
3. Martin JC, Davidson CJ, Pardyjak ER. Understanding sprint-cycling performance: the integration of muscle power, resistance, and modeling. Int J Sports Physiol Perform. 2007;2(1):5-21.
4. Kordi M, Folland J, Goodall S, et al. Mechanical and morphological determinants of peak power output in elite cyclists. Scand J Med Sci Sports. 2019.
5. Duche P, Ducher G, Lazzer S, Dore E, Tailhardat M, Bedu M. Peak power in obese and nonobese adolescents: effects of gender and braking force. Med Sci Sports Exerc. 2002;34(12):2072-2078.
6. Ronnestad BR, Hansen EA, Raastad T. Effect of heavy strength training on thigh muscle cross-sectional area, performance determinants, and performance in well-trained cyclists. Eur J Appl Physiol. 2010;108(5):965-975.
7. Driss T, Vandewalle H, Le Chevalier JM, Monod H. Force-velocity relationship on a cycle ergometer and knee-extensor strength indices. Can J Appl Physiol. 2002;27(3):250-262.
8. Ahtiainen JP, Pakarinen A, Alen M, Kraemer WJ, Hakkinen K. Muscle hypertrophy, hormonal adaptations and strength development during strength training in strength-trained and untrained men. Eur J Appl Physiol. 2003;89(6):555-563.
9. Suarez DG, Wagle JP, Cunanan AJ, Sausaman RW, Stone MH. Dynamic Correspondence of Resistance Training to Sport: A Brief Review. Strength and Conditioning Journal. 2019;41(4):80-88.
10. Young WB. Transfer of Strength and Power Training to Sports Performance. Int J Sport Physiol Perform. 2006;1(2):74-83.
11. Kordi M, Goodall S, Barratt P, Rowley N, Leeder J, Howatson G. Relation between Peak Power Output in Sprint Cycling and Maximum Voluntary Isometric Torque Production. J Electromyogr Kinesiol. 2017;35:95-99.
12. Thepaut-Mathieu C, Van Hoecke J, Maton B. Myoelectrical and mechanical changes linked to length specificity during isometric training. J Appl Physiol (1985). 1988;64(4):1500-1505.
13. Young K, McDonagh MJ, Davies CT. The effects of two forms of isometric training on the mechanical properties of the triceps surae in man. Pflugers Arch. 1985;405(4):384-388.
14. Lanza MB, Balshaw TG, Folland JP. Is the joint-angle specificity of isometric resistance training real? And if so, does it have a neural basis? Eur J Appl Physiol. 2019;119(11-12):2465-2476.
15. Graves JE, Pollock ML, Jones AE, Colvin AB, Leggett SH. Specificity of limited range of motion variable resistance training. Med Sci Sports Exerc. 1989;21(1):84-89.
16. Strojnik V, Komi PV. Neuromuscular fatigue after maximal stretch-shortening cycle exercise. J Appl Physiol (1985). 1998;84(1):344-350.
17. Maffiuletti NA, Aagaard P, Blazevich AJ, Folland J, Tillin N, Duchateau J. Rate of force development: physiological and methodological considerations. Eur J Appl Physiol. 2016;116(6):1091-1116.

18. Kordi M, Folland J, Goodall S, Barratt P, Howatson G. Reliability of traditional and task specific reference tasks to assess peak muscle activation during two different sprint cycling tests. J Electromyogr Kinesiol. 2019;46:41-48.
19. Arsac LM, Belli A, Lacour JR. Muscle function during brief maximal exercise: accurate measurements on a friction-loaded cycle ergometer. Eur J Appl Physiol Occup Physiol. 1996;74(1-2):100-106.
20. Gardner AS, Martin JC, Martin DT, Barras M, Jenkins DG. Maximal torque- and power-pedaling rate relationships for elite sprint cyclists in laboratory and field tests. Eur J Appl Physiol. 2007;101(3):287-292.
21. Kordi M, Folland J, Goodall S, Barratt P, Howatson G. Isovelocity vs. Isoinertial Sprint Cycling Tests for Power- and Torque-cadence Relationships. Int J Sports Med. 2019.
22. Hopkins WG. Spreadsheets for Analysis of Validity and Reliability. Sportscience. 2015;19:36-42.
23. Hopkins WG. Measures of reliability in sports medicine and science. Sports Med. 2000;30(1):1-15.
24. Duchateau J, Hainaut K. Isometric or dynamic training: differential effects on mechanical properties of a human muscle. J Appl Physiol Respir Environ Exerc Physiol. 1984;56(2):296-301.
25. Driss T, Vandewalle H. The measurement of maximal (anaerobic) power output on a cycle ergometer: a critical review. Biomed Res Int. 2013;2013:589361.
26. Andersen LL, Aagaard P. Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development. Eur J Appl Physiol. 2006;96(1):46-52.
27. Folland JP, Buckthorpe MW, Hannah R. Human capacity for explosive force production: neural and contractile determinants. Scand J Med Sci Sports. 2014;24(6):894-906.